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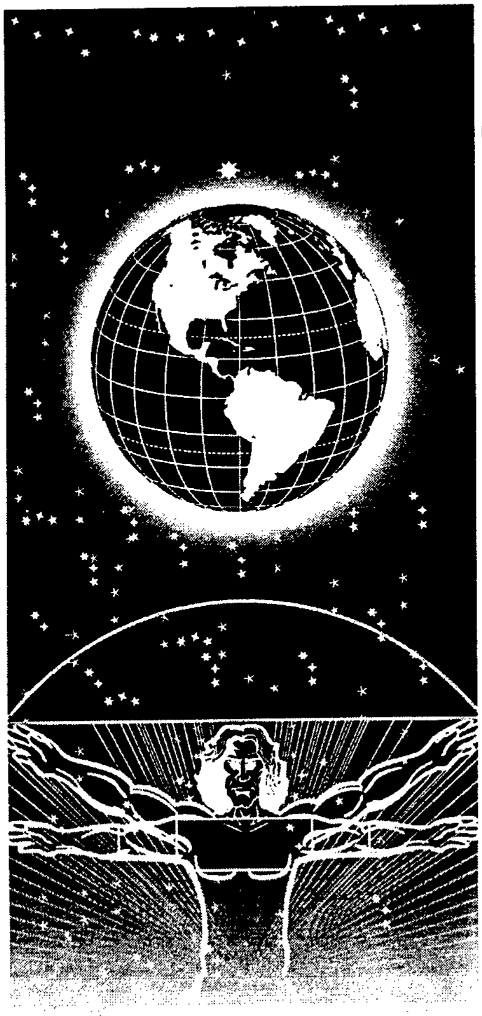

# UNITED STATES AIR FORCE RESEARCH LABORATORY

# A MATHEMATICAL MODEL OF A GIGAHERTZ TRANSVERSE ELECTROMAGNETIC CELL, I


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A mathematical model for transverse electromagnetic (TEM) cell has been constructed. The model estimates the electric field inside rectangular or flared TEM cells driven by a wideband electromagnetic current pulse. The finite difference time domain (FDTD) approach is used.

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## INTRODUCTION

The Gigahertz Transverse Electromagnetic Cell (GTEM) has become a popular tool in the electromagnetic compatibility community for testing radiated emission and immunity (susceptibility) work [5, 6, 13, 19]. Recently it has found use in the electromagnetic dosimetry community [8]. Whatever the application, it is important to know exactly what the field characteristics are inside the cell, both before and after a test object is placed in it. The field characteristics in an empty cell can be obtained by direct measurement. However, once an object is placed in the cell, the field is disturbed and it is no longer easy to know or even measure the field experienced by the object [14, 15, 16]. Mathematical modeling hence becomes indispensable. Using measurements from an empty cell, one can validate a mathematical model of the cell. Knowing the electrical properties of the object being tested, one can then estimate the field experienced by the test object using the model. Moreover, the scattered field from the object, if measured, can also be used to further validate the mathematical model.

Mathematical analysis of various aspects of GTEM cells can either be theoretical [11, 17, 18, 21, 22, 23, 28, 29, 31, 32] or computational (modeling) [9, 12, 16, 25]. Here we describe our initial efforts to model a 1.92m-long GTEM cell (Sandia National Laboratories, Albuqueque, New Mexico) using a finite difference time domain method. The GTEM cell modeled is part of an ultrawide-band (UWB) exposure system currently in use at U.S. Army-Medical Research and Material Command (USA-MCMR) to study the bioeffects of RF radiation in experimental animals. A precise knowledge of the electric field inside the test subject is required to calculate the energy absorption rate in the animal.

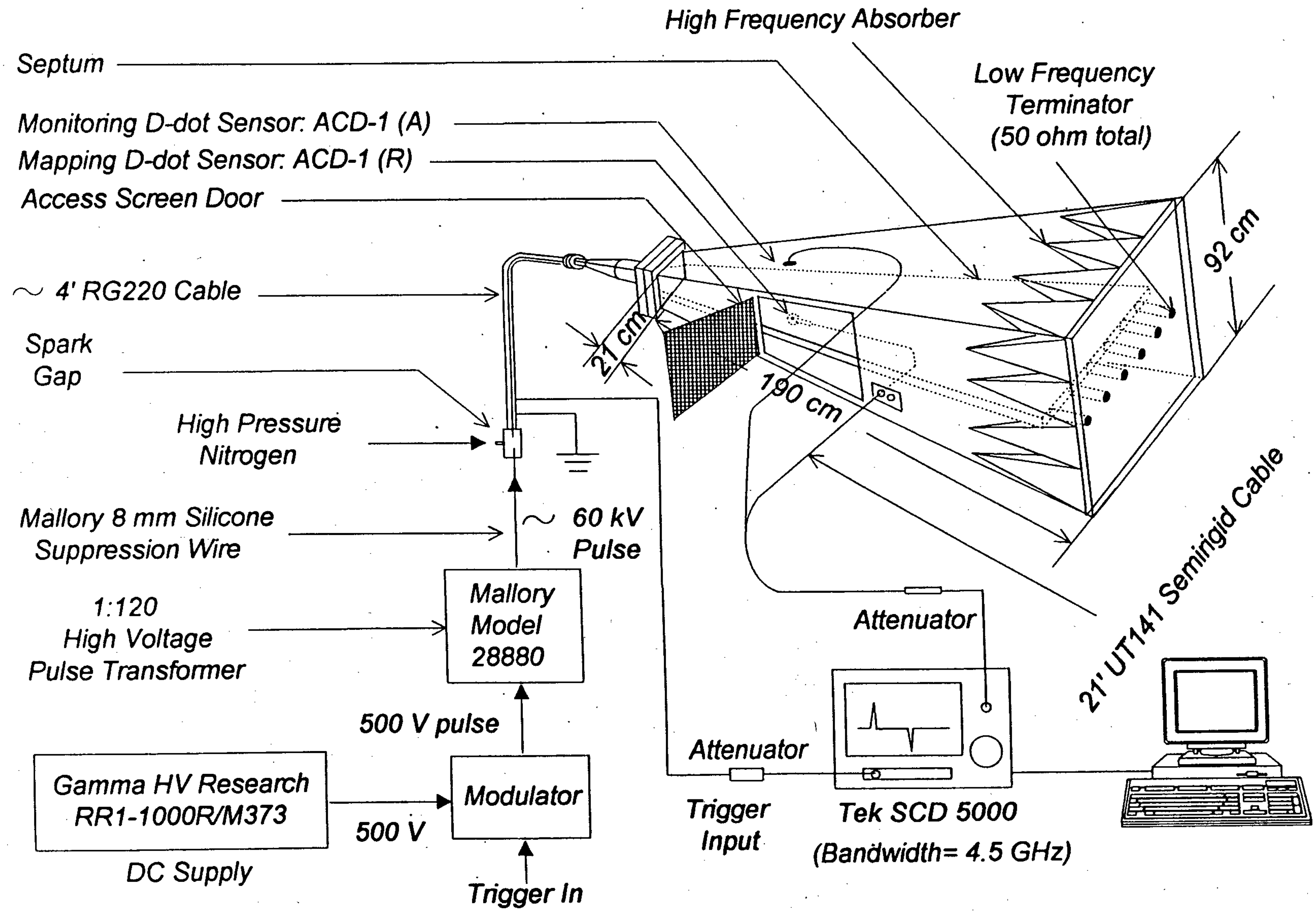


Figure 1: An Ultrawide-Band (UWB) Exposure Facility and Acquisition System

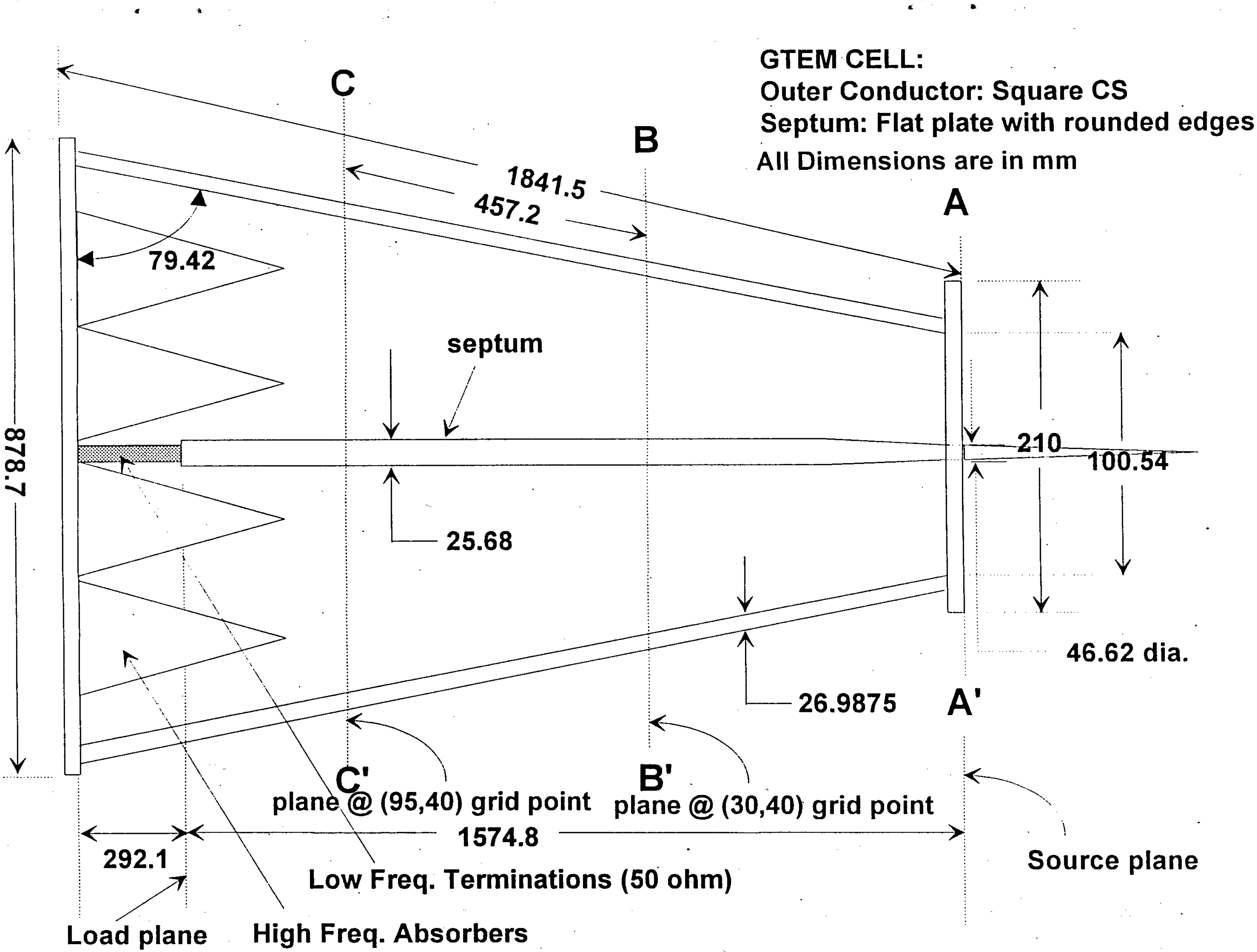


Figure 2 : GTEM Cell Cross Section (Vertical Plane)

# THE GTEM CELL

A detail description of the GTEM cell and related electronics and issues can be found in the references [1, 24]. A schematic of the UWB exposure facility and acquisition system is shown in Figure 1 and the dimensions of the GTEM Cell (in a vertical cross section) are shown in Figure 2.

# A MATHEMATICAL MODEL

To calculate the electromagnetic field inside the GTEM cell, we use a finite difference time domain (FDTD) code modified from Kunz and Luebbers [20]. This is basically the Yee's algorithm [30] enhanced with more recent treatment of absorbing boundary conditions [3, 4].

## A. Source

Instead of modeling the complete GTEM cell starting from the source (a spark-gap pulse generator) outside the main chamber, we assumed that the field inside the cell is driven by an equivalent source that is spread over an excitation plane (more precisely, a square annulus) located near the entrance to the cell. In particular, if the base plane (cross section AA' in Figure 2) of the cell is located at $z = 0$, then the excitation plane is assumed to be located at $z = z_e$ where $z_e$ has a magnitude equivalent to the thickness of a few Yee's cells. The excitation plane, a region $\Omega$ in the cross section of the GTEM cell at $z = z_e$, is depicted in Figure 3.

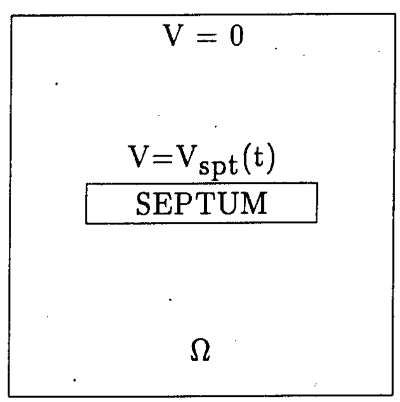


Figure 3: Excitation Plane $\Omega$. (Not to scale)

Assume, at a given time $t$, the inner rectangle, which corresponds to the septum of the GTEM cell, has a uniform voltage $V_{\text{spt}}(t)$ and the outer rectangle, which corresponds to the conductive walls of the cell, is grounded, then the electric field $\mathbf{E}^{\text{ex}}(x, y, z_e, t)$ in $\Omega$ induced by $V_{\text{spt}}(t)$ can be calculated by

$$\mathbf{E}^{\text{ex}}(x, y, z_e, t) = -\nabla\phi(x, y, t)$$

where the potential $\phi$ is the unique solution of the 2-dimensional Laplace's Equation

$$\nabla^2\phi = 0 \qquad \text{in } \Omega \tag{1}$$

subject to the boundary condition

$$\phi(x, y, t) = \begin{cases} V_{\text{spt}}(t) & \text{for } (x, y) \in \text{inner rectangle} \\ 0 & \text{for } (x, y) \in \text{outer rectangle} \end{cases}$$

It can easily be verified that if

$$V_{\text{spt}}(t) = V_m \cdot \Psi(t)$$

where $V_m$ is a constant and $\Psi(t)$ is an arbitrary function of $t$ and if $\phi_m(x, y)$ is the unique solution to Equation (1) subject to the boundary condition

$$\phi_m(x, y) = \begin{cases} V_m & \text{for } (x, y) \in \text{inner rectangle} \\ 0 & \text{for } (x, y) \in \text{outer rectangle} \end{cases}$$

then

$$\begin{aligned} \phi(x, y, t) &= \phi_m(x, y) \cdot \Psi(t) \\ \mathbf{E}^{\text{ex}}(x, y, z_e, t) &= -\nabla\phi(x, y, t) \\ &= -\Psi(t)\, \nabla\phi_m(x, y) \\ &= \Psi(t)\, \mathbf{E}_m^{\text{ex}}(x, y) \end{aligned}$$

where

$$\mathbf{E}_m^{\text{ex}}(x, y) := -\nabla\phi_m(x, y)$$

This implies that we only have to solve Equation (1) once for $\phi_m(x, y)$ to determine the excitation field $\mathbf{E}^{\text{ex}}(x, y, z_e, t)$ for all time $t$. Some additional discussion on the implementation of excitation sources in FDTD can be found in [2, 7].

## B. Boundary Conditions

The GTEM cell is terminated by an anechoic wall consisting of a series of resistive low frequency terminators and pyramidal microwave absorbers for the high frequency end of the frequency spectrum. These are constructed to minimize reflections at the terminal end that could compromise the field at a test site within the cell. We model this by placing a Berenger's perfectly matched layer (PML) [3, 4] at this terminal end to simulate non-reflection of electromagnetic waves. We also place a PML at the base plane (cross section AA' in Figure 2) to absorb fictitious backward waves generated by the assumed excitation plane. The four other walls of the GTEM cell are modeled faithfully as perfectly electrically conducting (PEC) boundary.

## C. Staircase Errors

The GTEM cell is flared. The side walls cannot all be aligned with the rectangular grid axes in FDTD. It is well known that this leads to so-called staircase errors in the computations. For the work reported here, we took the simple, albeit inefficient, approach of using smaller mesh sizes to minimize these errors. More sophisticated methods such as locally conforming FDTD schemes [26] will be used in the future.

# RESULTS

We have tested our computational method on several different TEM cells using a variety of input sources. The results have been excellent on simple cases and reasonable on more complex ones. We will report on two cases below.

## I. A Non-flared Square cell

In this computational experiment, we use the square TEM cell (the " NBS cell ") studied first experimentally by Crawford [10] and latter theoretically (quasi-statically) by Spiegel [27]. This square cell has dimensions shown in Figure 4.

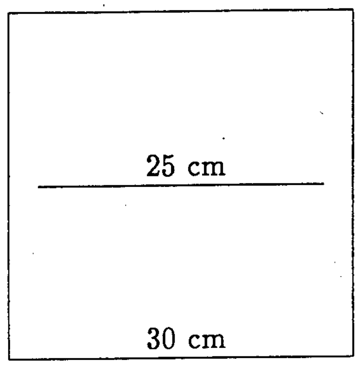


Figure 4: NBC Cell.

Unlike Spiegel's theoretical cell, the cell we studied has a finite non-zero thickness that is one FDTD cell thick. The FDTD cell we used is 5 mm thick. The input for this computational experiment is sinusoidal. Three frequencies were chosen: 100 MHz, 500 MHz, and 1 GHz. The cutoff frequency for the first order TE mode ($TE_{10}$) for this cell is slightly above 500 MHz [10].

We picked a the TEM cell that is 100 cm long (in the z-direction) and monitored the electric field at approximately the same locations where measurements were made by Crawford [10] and also by Spiegel, et al [27]. The cross section in which these points are taken is halfway ($z = 50$ cm) along the TEM cell. The results are shown in Figures 4 through 7. Figure 5 shows the potential field in the cross section at $z = 2.5$ cm. Figures 6 through 8 are the relative time-averaged magnitude of the electric field when using the frequencies 100 MHz, 500 MHz, and 1 GHz respectively. Also shown are the measured values. There is general agreement between the measured and the calculated. As expected, the first two calculated fields are practically identical, as they are both below cutoff.

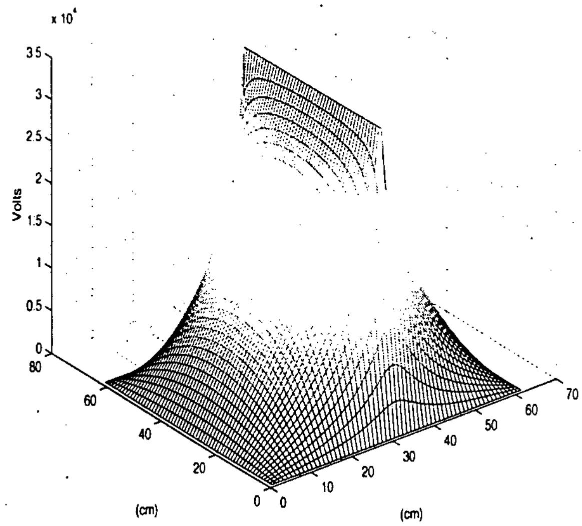


Figure 5: Potential (V) in Excitation Plane.

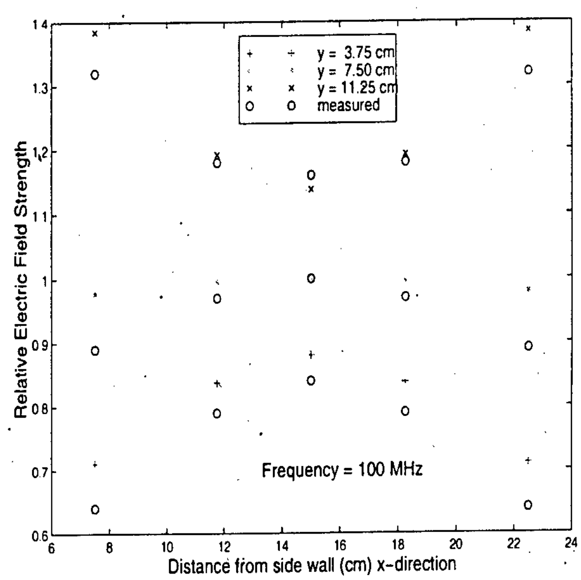


Figure 6: Calculated and Measured Relative E Field for 100 MHz Sinusoidal Input.

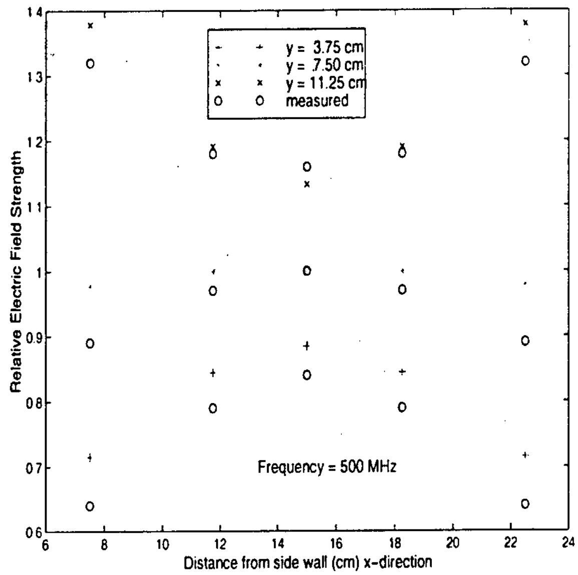


Figure 7: Calculated and Measured Relative E Field for 500 MHz Sinusoidal Input.

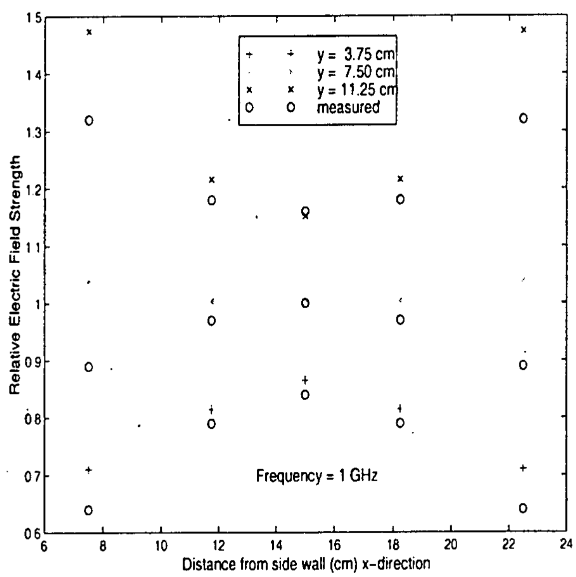


Figure 8: Calculated and Measured Relative E Field for 1 GHz Sinusoidal Input.

## II. A flared cell driven by a wide-band pulse

The GTEM cell shown in Figure 1 has dimensions shown in Figure 2 and Figure 10. The UWB pulse applied to the GTEM cell can be approximated by

$$V(t) = V_m \cdot \Psi(t)$$

where

$$\begin{aligned} V_m &= 130 \text{ kV} \\ \Psi(t) &= e^{-\alpha t} - e^{-\beta t} \\ \alpha &= 1.19661\text{E} + 9 \text{ s}^{-1} \\ \beta &= 1.99573\text{E} + 10 \text{ s}^{-1} \end{aligned}$$

This pulse has a rise time of 150 ps and a pulse width of 1 ns. This is depicted in Figure 11.

Setting $V_{\text{spt}}(t) = V_m$ and solving the Laplace's equation in Equation (1) yields the solution $\phi_m(x, y)$ similar in shape to that shown in Figure 5. The corresponding vector field $\mathbf{E}_m^{\text{ex}}(x, y)$ is shown in Figure 9.

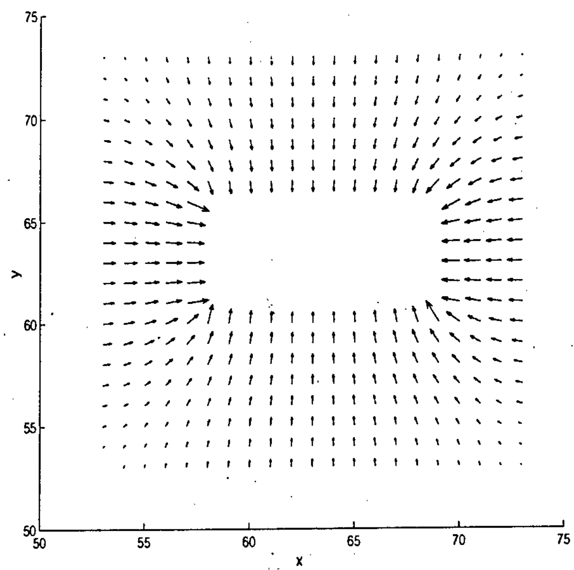


Figure 9: Calculated E Field in Excitation Plane for V=42.75 kV.

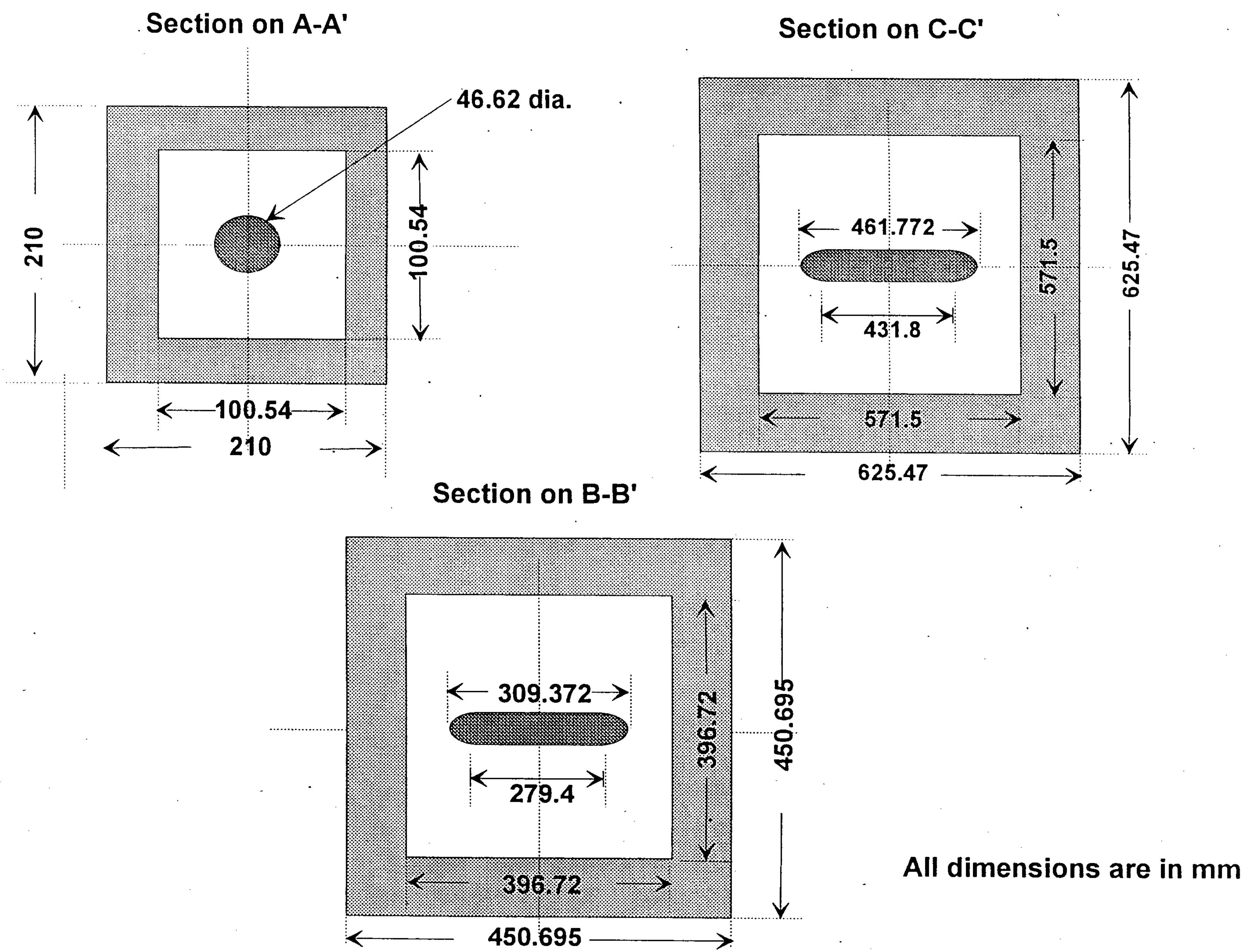


Figure 10: GTEM Cell Cross sections

Using this pulse, we calculated the field inside the cell using FDTD. The main parameters used are:

$$\begin{aligned} \text{space discretization: } \Delta x &= 0.005 \text{ m} \\ \text{space discretization: } \Delta y &= 0.005 \text{ m} \\ \text{space discretization: } \Delta z &= 0.005 \text{ m} \\ \text{time step: } \Delta t &= 9.629 \times 10^{-12} \text{sec} \end{aligned}$$

These values are dictated by the high frequency content of the pulse and the stability requirement of the method [20].

In our simulation, we calculated the **E** field at several points in the proximity of the location where the actual measurements had previously been taken. These selected points are in the center of cross section BB' (Figure 2) near the bottom of the cell. Figure 12 compares the calculated $E_y$ at the selected points to the measured $E_y$. The amplitude $V_m$ of the voltage source at the excitation plane was picked (trial and error) to be 42.75 kV in this particular calculation.

We have also measured and calculated several indices related to the **E** field at each point in a grid (not shown here) on the bottom wall ("parallel" to the septum). Among these indices is the peak intensity of the **E** field. From this a contour plot is made. This is shown in Figure 13. We used the model to calculate the peak **E** field intensity at approximately the same points and constructed the corresponding contour plot. This is shown in Figure 14. The two contour plots, Figure 13 and Figure 14 are qualitatively similar. (At this time, we have not fine tuned the choice of the amplitude $V_m$ of the voltage source at the excitation plane to make the comparison better.)

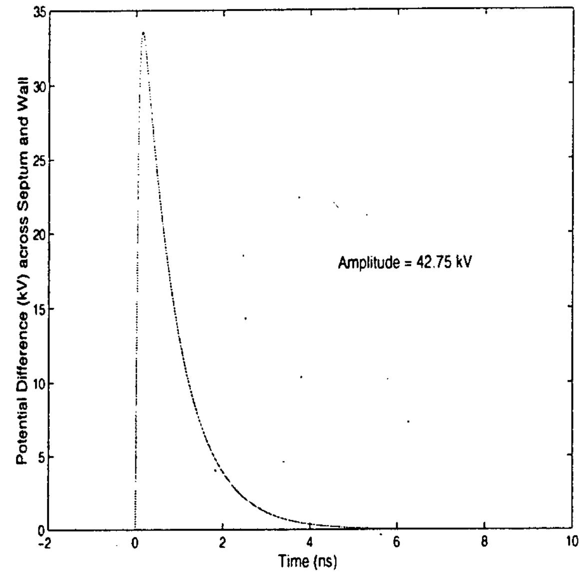


Figure 11: Simulated Input Voltage Source.

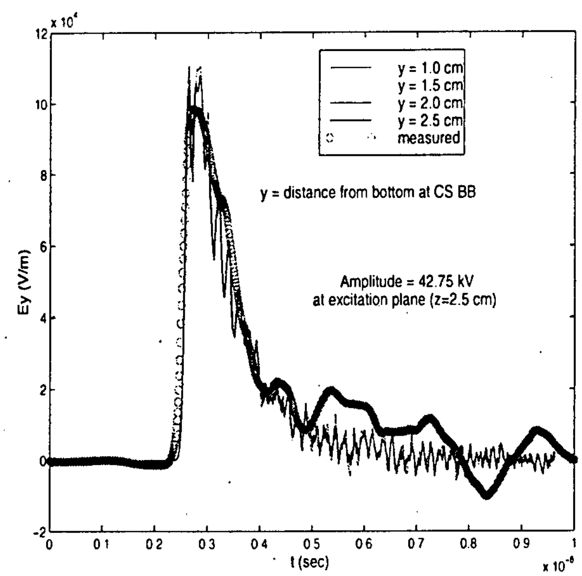


Figure 12: Calculated Ey at 4 points in CS BB vs Measured Ey.

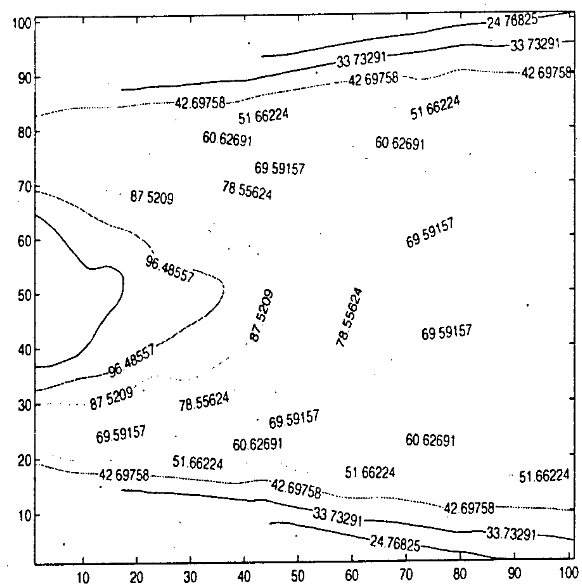


Figure 13: Contour Plot of Measured Peak E.

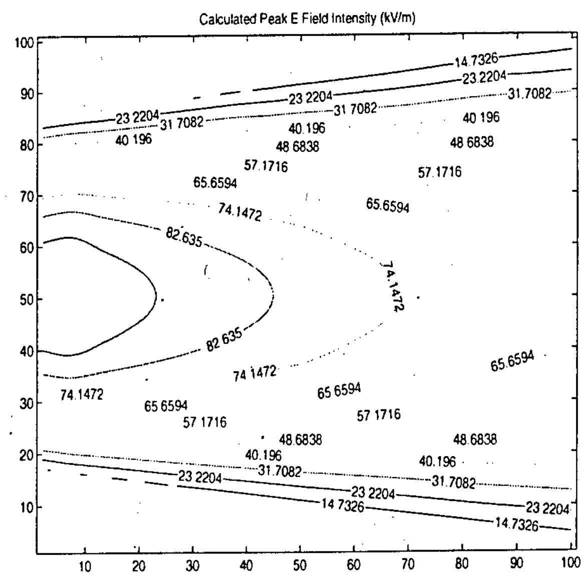


Figure 14: Contour Plot of Calculated Peak E.

# CONCLUSION

In this report we have described a general mathematical model that can be used to estimate the electric field in a large class of TEM cells. An excitation plane was used to simulate the input to the GTEM cell and the popular FDTD method was then used to calculate the field anywhere and anytime inside the cell. To our knowledge this is the first documented use of FDTD to model an ultrawide-band exposure system. We tested our model on the simple (square) NBC cell and on a flared GTEM cell. The results have been reasonable in all cases. We believe this effort has laid the foundation for further fruitful research. Future improvements to the model include implementing methods to reduce staircase errors and to allow for multiple grids. These improvements are necessary for the efficient and accurate modeling of relatively small objects placed in the cell. When accomplished, they will have increased the scope and capability of electromagnetic compatibility and dosimetry research.

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